RI 9566

REPORT OF INVESTIGATIONS/1995

Influence of Environmental Factors on Spark Ignition Probability

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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Report of Investigations 9566

Influence of Environmental Factors on Spark Ignition Probability

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere	pct	percent
cm^3/min	cubic centimeter per minute	psi	pound per square inch
kΩ	kilohm	psia	pound per square inch, absolute
m	meter	rpm	revolution per minute
mA	milliampere	s	second
mH	millihenry	V	volt
min	minute	V dc	volt, direct current
mm	millimeter	μF	microfarad
ms	millisecond	°C	degree celsius

INFLUENCE OF ENVIRONMENTAL FACTORS ON SPARK IGNITION PROBABILITY

By Jeffrey Shawn Peterson[1]

ABSTRACT

In past years, the U.S. Bureau of Mines has been involved in safety research that could ultimately relate the conditions of spark testing and actual use by estimating the simple ignition probability of a circuit in question. A major problem in estimating this probability is that results show a significant variability, even though gas mixtures and electrical parameters may be closely controlled.

Some researchers have suggested that the ambient environmental conditions of the testing may influence the results. A series of tests were conducted using a spark test apparatus to simulate a failing electrical circuit. By independently adjusting the temperature, pressure, or relative humidity of the combustible gas mixture, multiple test environments were examined. At each ignition, a computer recorded the temperature, pressure, and relative humidity of the gas immediately prior to the explosion. These data were then used to establish the effect of the test environment on the ignition probability and to create a mathematical model of the test environment's synergistic effects.

The analysis indicated that these effects were not as significant as previously expected. No general algorithm was found that could be used to predict these effects across the range of circuits tested.

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INTRODUCTION

As a result of the Coal Mine Health and Safety Act of 1969, reaffirmed by the Federal Mine Safety and Health Amendments Act of 1977, the U.S. Bureau of Mines (USBM) was directed to initiate research to reduce or eliminate hazards potentially harmful to the health and/or safety of the workplace for workers involved in mining or processing of minerals.

To create an explosion hazard, three elements must be present simultaneously: suspension of an ignitible fuel in air, confinement of this mixture, and an ignition source. In poorly ventilated areas, methane (CH_4) released during the mining process may accumulate in explosive concentrations, 5% to 15% CH_4 in air *(1)*[2] at atmospheric pressure and room temperature, and may then be ignited by a malfunctioning electrical device. The USBM research reported here concerns the testing of elemental circuits to determine the effect of the ambient environmental conditions on the probability of igniting such an atmosphere.

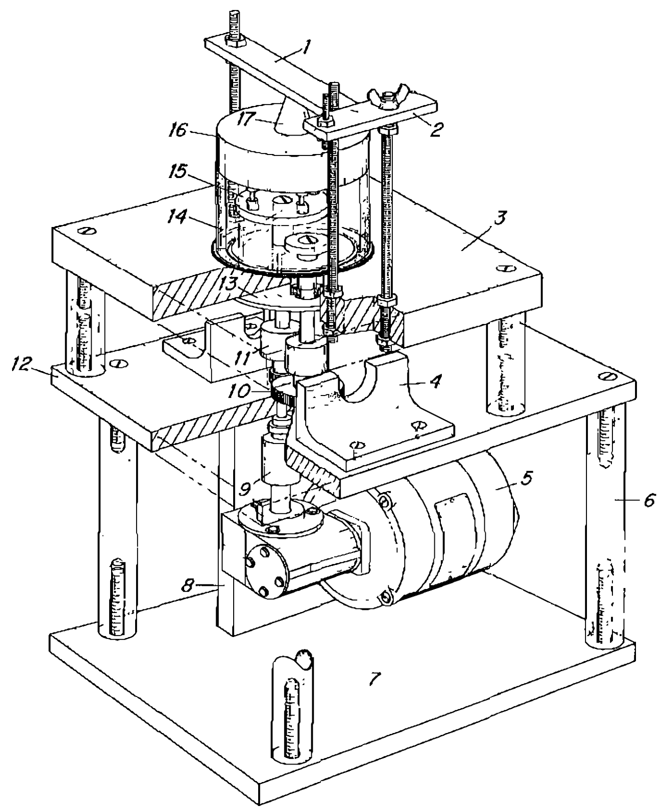
One of several techniques used to prevent explosions in hazardous areas is the testing of electrical circuits and devices for intrinsic safety (IS). However, because IS utilizes energy-limiting techniques, it is restricted in use to low-power applications. Other techniques, such as explosion-proof enclosures, require a physical barrier between the electrical circuit and the hazardous environment to contain an internal explosion.

By law, the Mine Safety and Health Administration (MSHA) must approve all devices intended for use in underground gassy mines inby the last open crosscut as described in Title 30, Code of Federal Regulations (30 CFR), Part 18.68 *(2)*. Other national IS standards, including the American National Standards Institute/Underwriters Laboratories (ANSI/UL) standard 913 *(3)* are used to supplement the requirements of 30 CFR. The ignition current-voltage curves available in ANSI/UL 913 are frequently referenced in the approvals process. Devices whose electrical circuits can be readily assessed in terms of elementary circuits may be evaluated for IS by comparison with the curves. Other devices are ignition tested using multiple scenarios under normal conditions. Additionally, a series of tests are conducted with 1.5 times the normal energy discharge and one worst case circuit fault and with normal energy discharge and two worst case circuit faults. If ignition does not occur during testing and the device meets certain construction requirements, it passes the IS test, but is not necessarily approved.

The USBM previously investigated the effect of voltage, current, inductance, and capacitance on the probability of igniting a CH_4-air mixture *(4)*. This research used the spark test apparatus (STA) (figure 1), a device similar to that used for the MSHA approvals tests. The general specifications for the USBM STA are detailed in International Electrotechnical Commission (IEC) Publication 79-3 *(5)*.

Test results using the STA vary significantly because ignitions occur on a random basis. Thus, to ensure repeatable results, large quantities of data are required to establish the statistical integrity of any data analysis. Because test-circuit characteristics and gas mixtures can be closely controlled, it has been suggested that the

Figure 1



KEY

1 Clamp
2 Latch
3 Upper plate
4 Brush bracket
5 Motor
6 Post
7 Base plate
8 Motor plate
9 Shaft adapter
10 Drive gear
11 Slip ring
12 Center plate
13 Bearing plate
14 Chamber
15 Whisker holder assembly
16 Chamber top
17 Chamber knob

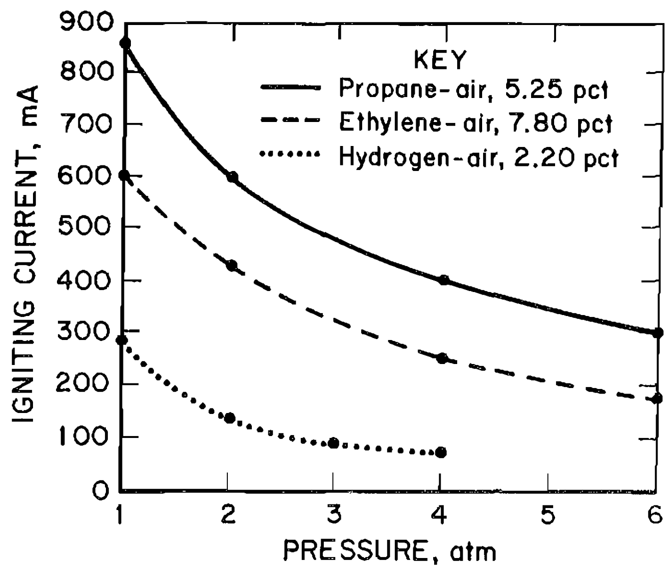
Spark test apparatus (STA) used to collect ignition data.

[2]Italic numbers in parentheses refer to references at the end of this report.

environment in which the testing takes place could have a profound effect on the results. Further, devices approved under a somewhat generic set of environmental conditions—room temperature; low, if any relative humidity (RH), and roughly one atmosphere of pressure—are often used under more diverse conditions. Obviously, the temperatures and RH in which a particular device would be expected to function would vary. Also, pressure increases roughly 1/2 psi for every 300 m of depth. Thus, conditions could vary not only day to day within a given mine, but from mine to mine as well.

Intuitively, the energy of a circuit under test would influence the probability of igniting the test gas. Magison's compilation of past research *(6, pp. 48-51)* has shown that the testing environment affects the energy necessary to induce an ignition. Consider two test volumes of gas: volume A at a higher temperature than volume B should require less energy input to raise the ignition kernel to its ignition temperature. The reverse would also be true. Similarly, the igniting current would vary depending upon the temperature of the surrounding gas mixture. Table 1 of this report shows minimum igniting currents for a 24-V, 1-m H circuit using three fuel-air mixtures, and tested at 20 and 200 °C *(6, p. 50)*. A similar relationship exists between the igniting current and pressure. The number of gas molecules per unit volume is roughly proportional to pressure. Decreasing pressure decreases the energy-per-unit volume produced by combustion and slows down the heat transfer within a gas. Thus, a compressed volume is more easily ignited than a similar volume at a lower pressure. This is illustrated graphically in figure 2 *(6, p. 52)*, which shows the variation of minimum igniting current with pressure for the same gas mixtures as mentioned earlier. A dry volume of gas would require less energy input to reach its ignition temperature than a wetted volume because water vapor slows heat transfer within a gas, effectively limiting propagation of combustion. The synergistic effect of these factors on igniting a CH_4-air mixture is not yet understood. This research studies and quantifies these effects on a probabilistic basis.

Figure 2



Effect of pressure on igniting current. (Reprinted by permission of Instrument Society of America, from Electrical Instruments in Hazardous Locations, Third Revised Edition. Copyright 1978.)

Table 1.—Effect of temperature on minimum igniting current

Mixture, %	Minimum igniting current, mA	
	20 °C	200 °C
Ethylene-air, 7.8 . . .	600	500
Hydrogen-air, 2.2 . .	280	200
Propane-air, 5.25 . .	850	800

Source: Instrument Society of America. From *Electrical Instruments in Hazardous Locations, Third Revised Edition.* Copyright 1978; reprinted by permission.

METHOD OF EXPERIMENT

GENERAL

The STA can be used to simulate a failing or shorted electrical circuit. It employs two counter-rotating cylindrical shafts that extend into a small explosion chamber that is filled with a combustible mixture of gases. The shafts are geared so that shaft speeds vary in a ratio of 50:12. Under usual circumstances, the drive shaft would be set at 80 rpm. Secured to the top of the drive shaft is an electrode holder. Suspended from this holder are four tungsten wire electrodes with an unsupported length of 11 mm and a diameter of 0.0203 mm *(3, p. 39)*. To prevent failing under test conditions, the electrodes are annealed prior to use *(5, p. 15)*. Still, the wire splinters, breaks, and/or simply wears short and thus requires replacement after 1,000 sparks per electrode or if any two fail, whichever occurs first. A cadmium disk electrode is secured atop the second shaft (figure 3) *(5, p. 17)*. Its top surface lies 10 mm below the wire electrode holder, ensuring a 1-mm overlap with the tungsten wire. Because ignitions are less likely to occur when using a new disk, a 20-min disk break-in period in an unenergized circuit is recommended. The STA shafts are connected electrically to an external circuit via a slip ring assembly. As the shafts rotate, the tungsten wire drags across the cadmium disk. The external circuit is interrupted, creating sparks that may or may not ignite the gas in the surrounding explosion chamber, depending upon the available circuit energy at the point of test.

Determining the test environments was crucial to the experiment. The majority of temperatures commonly found in a typical mining environment fall within a 10 to 50 °C range. However, because of time constraints, testing was limited to 25 and 50±5.0 °C. The ambient pressure in the Pittsburgh area, typically 13.9 to 14.4 psia was used as one test pressure and comprised the majority of tests conducted. Other tests were conducted at 20±0.2 psia (roughly 3,200-m depth below sea level). Owing to time constraints, a few tests at 10±0.2 psia (2,800-m elevation above sea level) were conducted. The bottled gas used in the experiment was dry on the order of parts per million water vapor, thus 0% + 5% served as the low test RH. Other test RH's were 40% and 70±5%. Various combinations of these temperatures, pressures, and RH's were used to formulate the testing environments.

Testing was conducted at the most easily ignitible concentration of CH_4 in air, 8.3±0.3% (*6, p. 96*). For practical purposes, this value can be considered a constant, varying only slightly depending on the nature of the experiment (*6, p. 47*). Under normal circumstances, such a mixture would contain 19.2% oxygen (O_2). To conduct a worst case analysis, the O_2 concentration was increased to 20.0±0.1%.

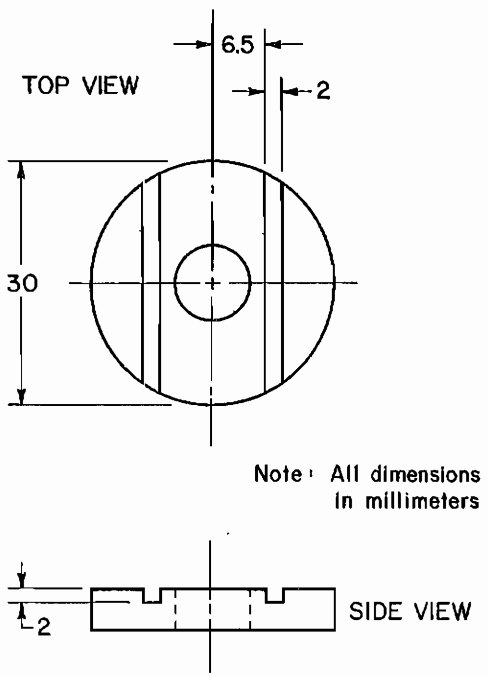
Simple series and parallel circuits as shown in figures 4 to 6, were tested. The test circuit component characteristics are shown below in table 2. Noninductively wound resistors were used to limit current in all tests. For resistor circuits, testing below 20 V dc would make it necessary to use currents of such magnitude that hot wire ignitions could be induced and skew the test results. The inductor circuit was powered by a 24-V dc source and employed air core inductors. Aluminum electrolytic capacitors were used in the parallel capacitor circuit. These were chosen because they are commonly used for large-value capacitors in electronic construction. It was essential that the capacitor fully charge to maintain the integrity of the tests. The charging resistor was chosen to provide a charging time constant of 100 ms. Also, only one tungsten-wire electrode was used and the STA rotation speed was reduced so the capacitor could charge for roughly five time constants. The charge-discharge cycle of the capacitor was monitored with an oscilloscope to ensure full charging of the capacitor.

Table 2.—Test circuit characteristics

Resistor		Inductor		Capacitor		
Voltage, V dc	Current, mA	L,[1] mH	Current, mA	C,[2] µF	Voltage, V dc	Charging R,[3] kΩ
20	3,480	1	911	1.2	110	83.3
30	827	10	288	10.3	40	9.71
40	364	100	100	107.0	21	0.935
50	314	600	54	1,310.0	14	0.076

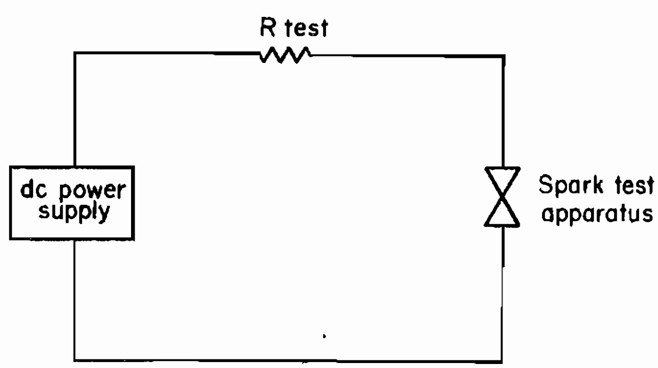
[1]Inductance.
[2]Capacitance.
[3]Resistance.

Figure 3



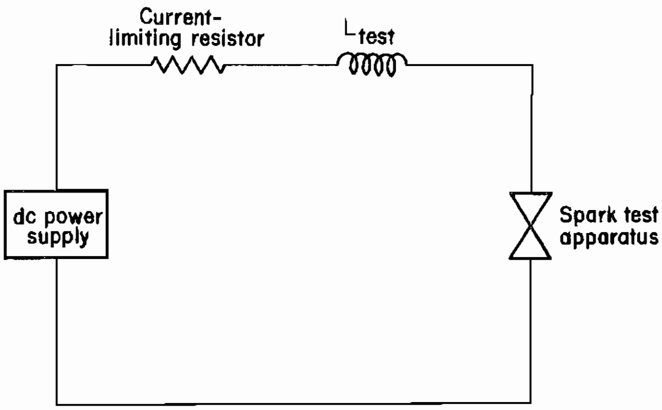
STA cadmium disk electrode.

Figure 4



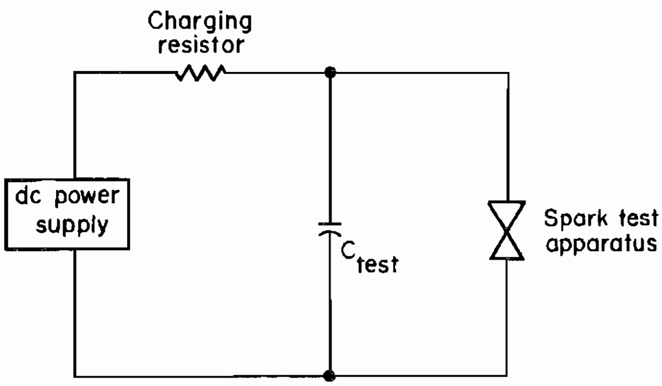
Resistor test circuit used to obtain spark ignition data.

Figure 5



Inductor test circuit used to obtain spark ignition data.

Figure 6



Capacitor test circuit used to obtain spark ignition data.

The tungsten-wire electrodes were replaced whenever the first of two conditions occurred. They were changed every 4,000 to 5,000 sparks when conducting resistor or inductor circuit tests and every 1,000 sparks when conducting capacitor circuit tests, or after four or five ignitions. This prevented a particular set of electrodes from unduly influencing test results. Earlier research indicated that electrode condition alone could influence research results *(7, pp. 74-77)*.

Many possible test combinations were available. As an example, a 10.3-μF, 40-V dc test could be conducted with environmental conditions of 25 °C, ambient pressure, and 0% RH. Then the test could be repeated by raising the pressure to 20 psia or by raising the RH to 40%.

Because the existing STA machine could not hold pressure or a partial vacuum, it was necessary to design a new device (figure 7). It was imperative to keep the new design as similar as possible to the standard device so that the testing results would not be adversely affected. The explosion chamber, its baseplate, and the shafts of the old STA were replaced. The existing drive motor, base platform, electrodes, etc., were still used.

Determining a method to seal around the rotating shafts for both positive and negative pressure was of primary importance. A graphite ribbon 6.35 mm wide and 0.381 mm thick was finally chosen as the shaft seal medium. This substance is traditionally used as valve packing, but it served this purpose well. The ribbon is simply wrapped around the shaft and then packed. This process was repeated several times to fill the stuffing box and ensure a proper seal. Usually, only two packings were required.

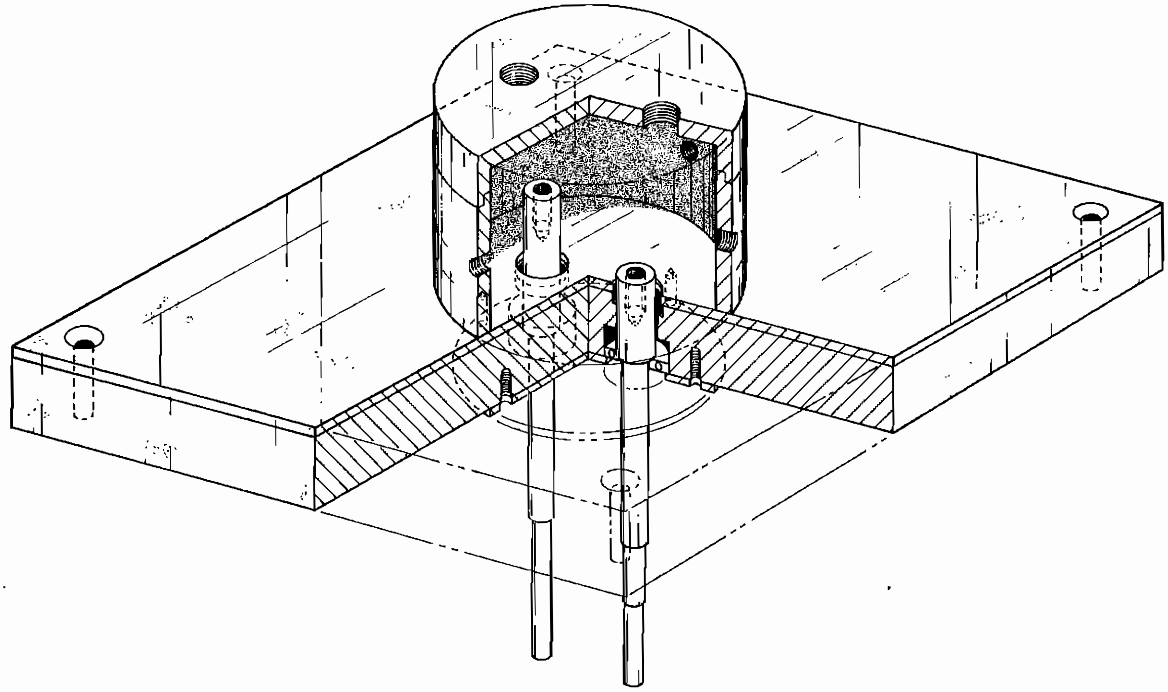
Because two separate test setups were used for the ambient pressure tests and those conducted at 10 or 20 psia, each will be discussed separately.

TESTS—AMBIENT PRESSURE

The mixed gas was delivered at roughly 1,120 to 1,150 cm^3/min (figure 8). Of the mixed gas, 400 to 500 cm^3/min were delivered to the STA, 200 cm^3/min to the O_2 analyzer, and the remainder to the CH_4 analyzer. Because only ambient pressure tests were conducted with this setup, no pressure compensation was required. Because the temperature in the laboratory was usually 20 to 26 °C, temperature adjustment was rarely required for the 25 °C tests. For the 50 °C tests, a system of heating tapes wrapped around the explosion chamber and gas lines was used to heat the gas. By controlling the voltage to the tapes via a variac, the temperature was adjusted. The test gas was wetted by diverting a portion of it through a gas-washing bottle (GWB). A GWB is a glass cylinder in which gas enters, travels to the bottom of the bottle through glass tubing, and exits the tubing through a fritted disk. The fritted disk serves to breakup the gas into small bubbles, increasing the surface area to more easily transfer the water to the gas. The gas then bubbles up the column of water and out of the GWB. The wetted gas was then mixed with the remaining dry gas before entering the STA explosion chamber. By varying the percentage of gas flowing through the GWB, any value RH could be obtained. If RH tests were being conducted at 50 °C, the GWB was also wrapped in a heating tape and placed upon a hotplate to heat the water within.

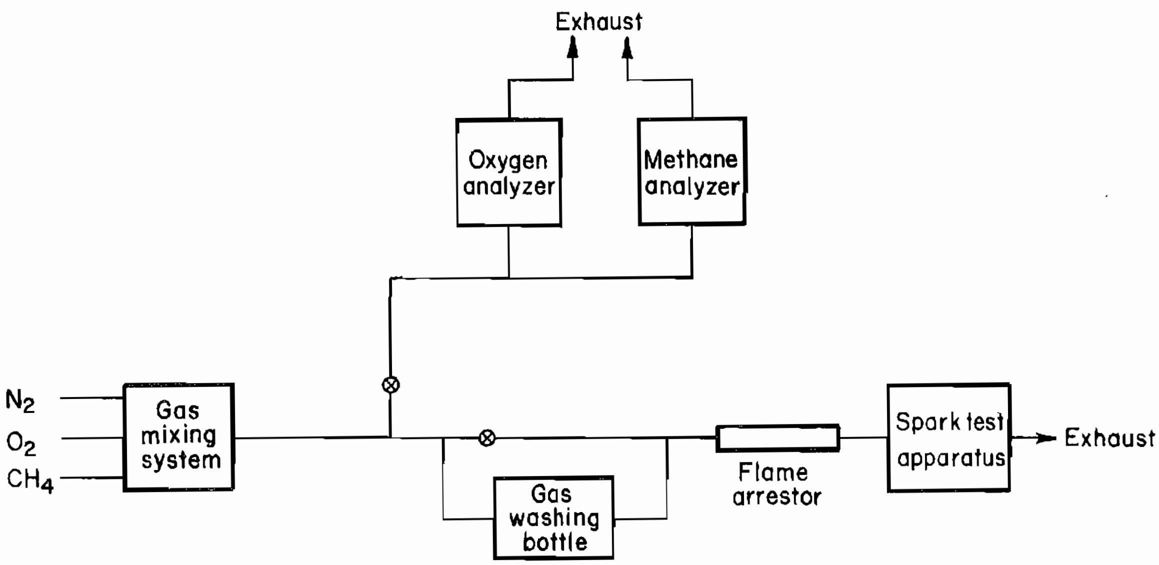
The aforementioned gas concentrations were for conducting dry tests, but there is more to consider when conducting wetted tests. The water vapor in a wetted volume would effectively reduce the concentrations of CH_4 and O_2. The instrumentation used to monitor the gas concentrations was designed for dry samples only. Calculations were made to determine what dry concentrations of CH_4 and O_2 would meet the above criteria in wetted, mixed samples at 40% and 70% RH at the temperatures and pressures tested. Results are shown in table 3.

Figure 7



STA design for pressurized and partial vacuum testing.

Figure 8



STA ambient pressure test gas delivery system.

Table 3.—Gas concentrations for RH tests at ambient pressure, percent

RH	O_2	CH_4
0	19.9-20.1	8.0-8.6
40	20.2-20.4	8.2-8.6
70	20.4-20.6	8.3-8.7

TESTS—10 AND 20 PSIA

The 10 and 20 psia tests were conducted statically or without constant gas flow. A system of valves was set up to mix the gases (figure 9). The explosion chamber was filled using Dalton's Law of Partial Pressures. This law states that the pressure exerted by each gas in a mixture is its partial pressure, and the total pressure of the mixture of gases is the sum of the partial pressures of all gases present. Table 4 illustrates the partial pressures attributable to each gas for 10 and 20 psia tests for the appropriate concentrations. The partial pressures listed in table 4 are good for dry samples only. When conducting wetted tests, the partial pressure of the water vapor would normally be taken into consideration. For these tests, it was considered to be of the utmost importance that CH_4 and O_2 concentrations remain consistent from test to test. Thus, the same partial pressures of CH_4 and O_2 were added in both dry and wetted tests. Random samples of the mixed gas were taken for spectrographic analysis to ensure that the gases were mixed in the correct quantities.

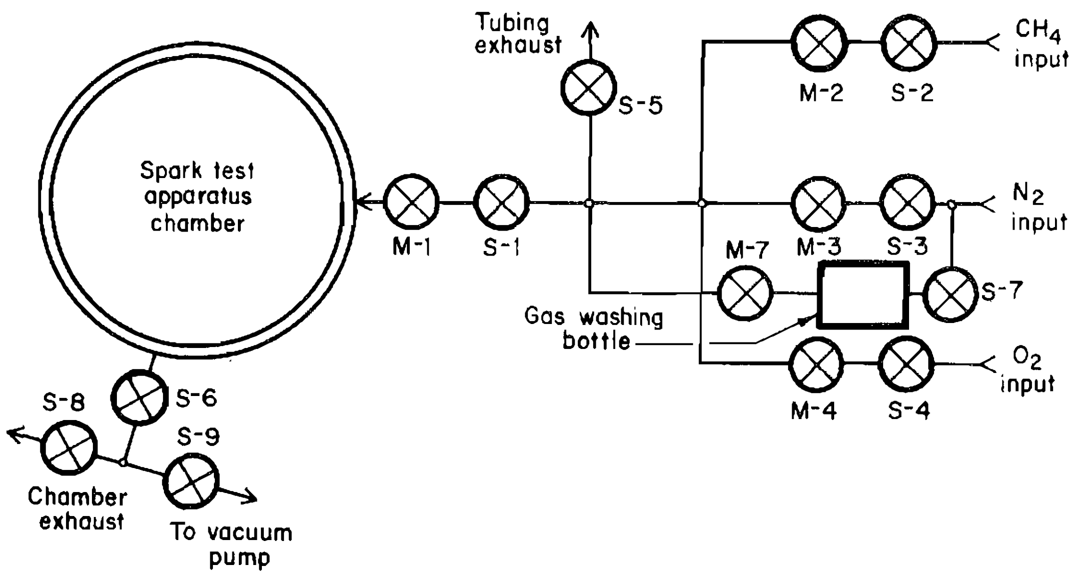
Table 4.—Component gas partial pressures for 10- and 20-psia tests

Gas	10 psia	20 psia
N_2	7.2	14.3
O_2	2.0	4.0
CH_4	0.8	1.7

Initially, the explosion chamber was purged with nitrogen (N_2). The chamber was sealed, and the chamber inlet lines were purged with CH_4. The proper amount of CH_4 was then added and the chamber was again sealed. The chamber inlet lines were then purged with O_2. The proper amount of O_2 was added and the chamber sealed again. Finally, any N_2 necessary to raise the pressure to 20 psia was added. If conducting 10 psia tests, the explosion chamber was then partially evacuated using a vacuum pump.

This details the method used to set and maintain the pressure. Methods to control the temperature and RH were similar to those employed for the ambient pressure tests.

Figure 9



KEY

M-1 Chamber input metering valve
M-2 Methane metering valve
M-3 Nitrogen metering valve
M-4 Oxygen metering valve
M-7 Gas washing bottle output valve
S-1 Chamber input shut-off valve
S-2 Methane shut-off valve
S-3 Nitrogen shut-off valve
S-4 Oxygen shut-off valve
S-5 Tubing exhaust (purge) shut-off valve
S-6 Chamber exhaust shut-off valve
S-7 Gas washing bottle input valve
S-8 Chamber exhaust valve
S-9 Vacuum pump shut-off valve

STA 10 and 20 psia test gas delivery system.

METHOD OF DATA COLLECTION

The environment sensor devices employed were as follows: an absolute pressure transducer with an operating range of 0 to 100 psia, a RH-temperature sensor with ranges of 0% to 100% RH and -20 to 80 °C (for 10 and 20 psia tests), and a T-type thermocouple (for ambient pressure tests). Each was connected to a digital panel meter to provide a visual readout of the test environment. Each panel meter had analog outputs that were proportional to real units. These signals were passed to two expansion boards. These boards provided signal gain and conditioning of the signals before the readings were sampled by an analog-to-digital converter (ADC) installed in a personal computer (PC). The ADC was controlled by a BASIC computer program. Every 2 s, the ADC sampled the test environment and temporarily stored the temperature, pressure, and RH as variables.

Two pressure switches were attached to the STA explosion chamber. At an ignition (increase in pressure), the switches opened. The first switch interrupted power to the STA motor, halting the shaft rotation. Delay circuitry provided a variable shutdown period to allow the system to purge the burned gas and/or to allow the explosion chamber to be refilled. The system could then automatically restart. The second pressure switch triggered the ADC with a 0.4-V dc signal. The program then stored the date, time, the ignition number, and most current environment readings in a data file. This information was then displayed on the PC screen (figure 10). The test operator then entered the day's spark count for the particular test so that, during the analysis stage, a probability of ignition (p_i) could be associated with each ignition and the data file. The p_i was defined as

$$p_i = \# \text{ of ignitions}/\# \text{ of sparks.} \qquad (1)$$

The spark count was saved and the ignition information was tagged so that it could not be accidentally overwritten. Each data file consisted of 25 ignitions and was circuit and environment specific. As an example, the data file shown in figure 10 is a resistor circuit test conducted at 40 V dc, 364 mA, and in a test environment of 25 °C, ambient pressure, and 70% RH. During testing, 89 such files were generated including 34 resistor, 31 capacitor, and 24 inductor tests. An example of a partial data file is shown in figure 11.

Figure 10

10-18-92 08:09:24

R40AF 40 V dc 364 mA

Temperature - 21.4 °C Relative humidity - 65.8 pct

Pressure - 14.0 psia

Ignition number - 1 Enter today's spark count -

Example computer screen immediately after test gas ignition.

Figure 11

DATAFILE R40AF

IG No.	Date	Time	Temp, °C	Pressure, psia	Pct RH	V dc	mA	Sparks
1	10-18-92	08:09:24	21.4	14.0	65.8	40	364	254
2	10-18-92	08:17:23	21.4	14.0	71.3	40	364	838
3	10-18-92	08:24:24	22.3	13.9	68.7	40	364	1,139
4	10-18-92	08:31:27	22.2	13.9	66.8	40	364	1,457
5	10-18-92	08:38:25	22.3	14.0	68.7	40	364	1,749
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

Example of partial test data file.

METHOD OF COMPUTER ANALYSIS

Data were analyzed on a circuit-specific basis. All resistor circuit test results were examined as a group, as were the results of the inductor and capacitor circuit tests. For each particular circuit, a summary table was created listing the average temperature, pressure, and RH of the data files as well as the p_i. The log of the p_i was used as the fourth variable in the final analysis.

One method to determine the effect that one variable has on another is to calculate their linear correlation. By definition, the linear correlation represents the extent of the linear association between two variables. These values are bounded by ±1. Positive correlations indicate that an increase in one variable results in an increase in the other. The reverse would be true for negative correlations. As the magnitude of correlation approaches one, the variables are more strongly correlated. Correlations near zero, then, indicate little relationship between the variables. Conventional thinking would suggest that the temperature and pressure would be positively correlated with the probability of ignition, or log of p_i in this analysis, while the reverse would be true for the RH.

Multiple linear regression analysis was used to generate linear coefficients relating the environmental variables to the log of the p_i. Such analysis summarizes how much each variable contributes to a mathematical model of the results. A backwards, stepwise multiple regression was performed on each circuit's summary table. In such analysis, all the variables are included in the model and then the variable that contributes the least to the model may be eliminated individually. Each cycle through the analysis generates a coefficient of determination (R^2). This represents the percentage of the variation in the response explained by the regression model and can be used to measure the goodness of fit. Its value is bounded by zero and one. As variables are eliminated, the R^2 value decreases by varying degrees, depending upon the data. For this analysis, variables were eliminated until the change in the R^2 value was greater than 0.05, or stated another way, a variable was eliminated when its effect accounted for less than 5% of the variability of the dependent variable (log p_i). Decreases larger than 5% indicated that the variable contributed enough to the model to be included. The regression analysis yielded an equation for the model:

$$\log p_i = X_1(T) + X_2(P) + X_3(RH) + X_4 \tag{2}$$

or, equivalently,

$$p_i = 10^{(X_1(T) + X_2(P) + X_3(RH) + (X_4))}, \tag{3}$$

where p_i = probability of ignition,

T = temperature, °C,

P = pressure, psia,

RH = relative humidity expressed as a percentage,

and X_1 through X_4 are coefficients generated during the analysis.

TEST RESULTS AND ANALYSIS

As mentioned earlier, conventional thinking would suggest that the temperature and pressure would be positively correlated with the log of p_i while the reverse would be true for the RH. The test environment observed correlations are listed in table 5. In most of the cases, the observed correlations were significant only in that they are of the opposite sign than expected or their magnitude is low. Two of the three temperature correlations are negative, contrary to the initial hypothesis. The pressure and RH correlations were, as expected, positive and negative, respectively.

A magnitude for the true correlation can be estimated for a given confidence level. This true correlation is the minimum value of the magnitude of an observed correlation, given sample size and number of independent variables. This, in turn, provides a measure of reliability of the observed correlations *(8)*. Here, the sample size is the number of data files generated for a particular type of circuit. As mentioned previously, there were 34 files of data generated for resistor circuits, 31 for capacitor circuits, and 24 for inductor circuits. The number of independent variables for each data file was three—average temperature, pressure, and relative humidity.

Table 5.—Test circuit observed correlations

Circuit	Observed correlation with log of p_i		
	Temperature	Pressure	RH
Capacitor	-0.02	0.62	-0.55
Inductor	0.06	0.61	-0.14
Resistor	-0.34	0.04	-0.52

p_i Probability of ignition.
RH Relative humidity.

The magnitudes of the observed correlations for true correlations of 0.30 and 0.50 are listed for the respective test circuits in table 6. These values are given for a confidence level of 95% (i.e., in 19 of 20 instances they will be true). As an example, if the observed correlation for a resistor circuit variable is given as 0.72, then with 95% confidence, its true correlation will be at least 0.50. Using this as a method to test for the significance of the observed correlations, none of those listed in table 5 are significant for a true correlation of 0.50. If the true correlation is reduced to 0.30, only the capacitor circuit pressure observed correlation meets the above criteria. Further, no particular environmental variable's observed correlation was consistent for the three types of circuits tested. All of this indicates that none of the environmental variables correlated significantly with the log of the p_i.

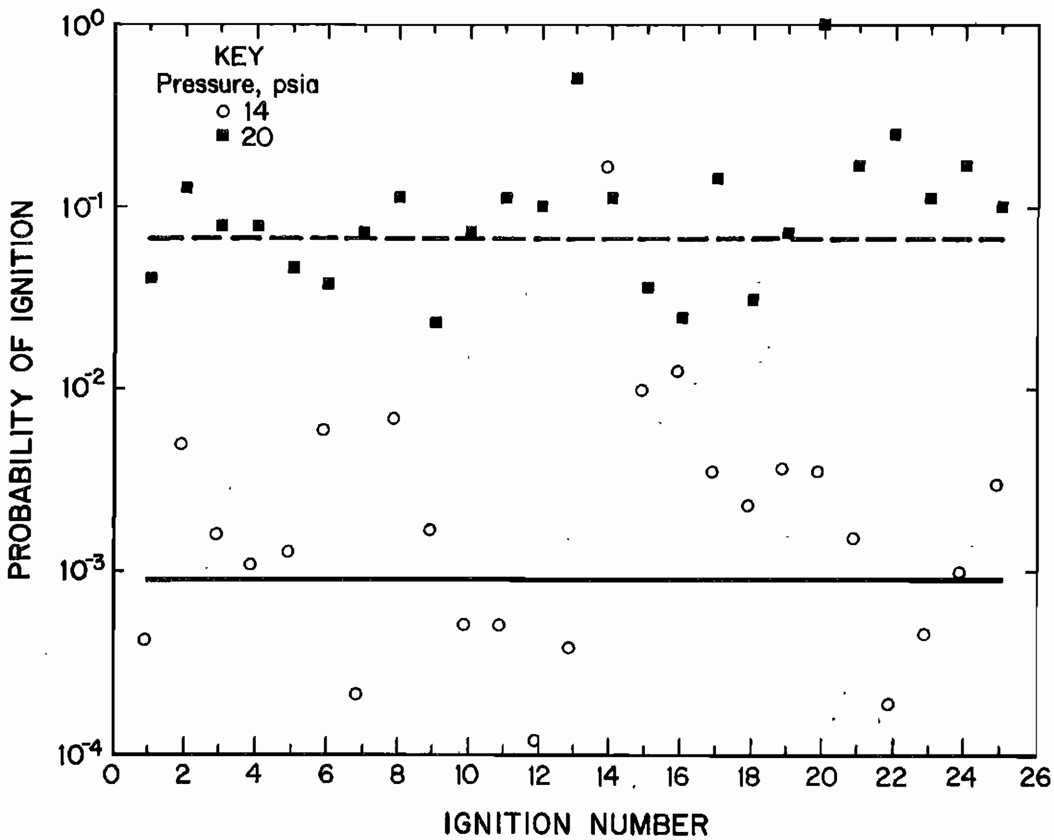
Table 6.—Observed correlations for true correlations of 0.30 and 0.50

Circuit	True correlations	
	0.30	0.50
Capacitor . . .	0.60	0.73
Inductor	0.65	0.77
Resistor	0.58	0.72

Correlation values alone cannot determine the relationships sought. For each ignition in a data file, a probability was calculated by using equation 1 for the number of sparks required to produce that particular ignition. Scatterplots generated from the data showing this p_i versus its corresponding ignition number were generated. Figure 12 shows two inductor circuit test results. Both were conducted at 10 mH, 288 mA, 25 °C, and 40% RH. Only the test pressures are different; one test was conducted at ambient pressure, the other at 20 psia. It was expected that the 20-psia test would require less energy to ignite the volume of gas and thus should illustrate a trend of increased probabilities relative to the ambient pressure test. Figure 12 is a clear example of this expected result. As shown, the probabilities of the 20 psia tests all lie above the 0.01 probability level (one ignition per 100 sparks). Only two of the 25 ignitions of the ambient pressure test lie above this level, i.e., fewer than 100 sparks were required to produce the next ignition in the test. For reference purposes, the cumulative p_i for the ambient pressure data file (p_i = 0.000903), and the 20 psia data file (p_i = 0.0661), are also shown.

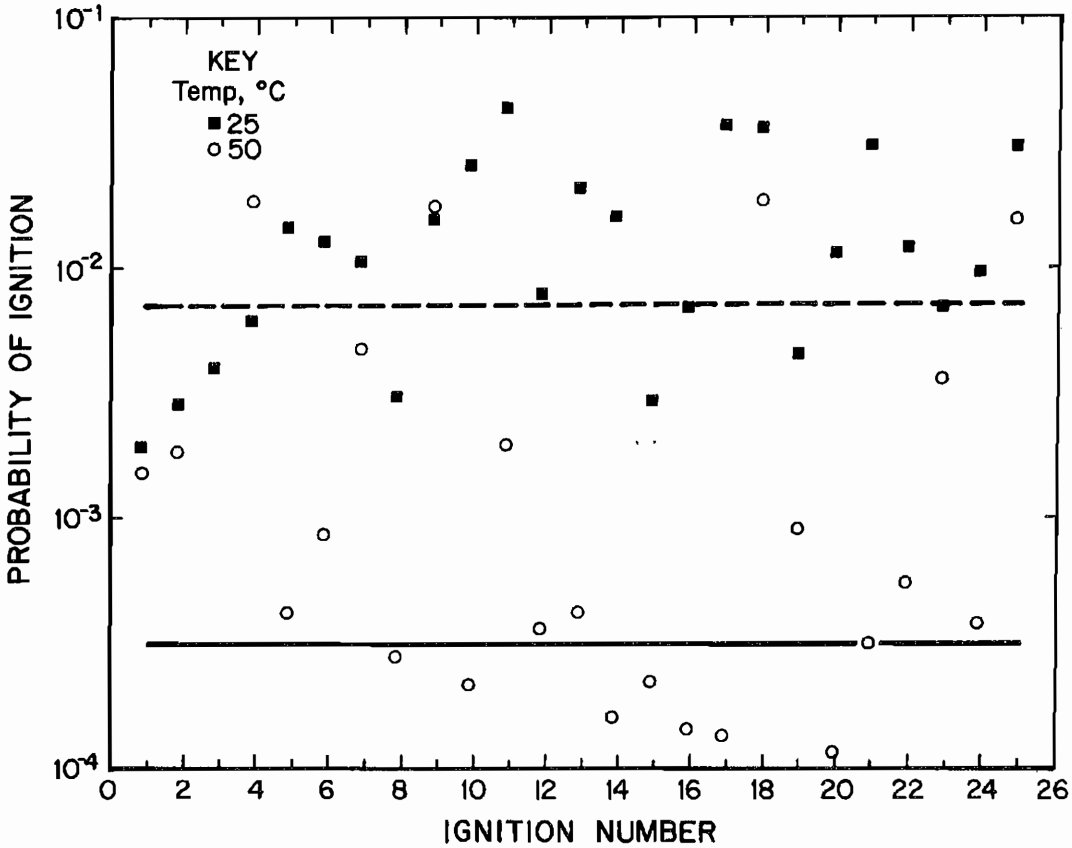
Figure 13 illustrates results for two resistor circuit data files. Both tests were conducted at 30 V dc, 827 mA, ambient pressure, and 70% RH. The only difference was that

Figure 12



Scatterplot of expected results of p_i versus ignition number for two tests.

Figure 13

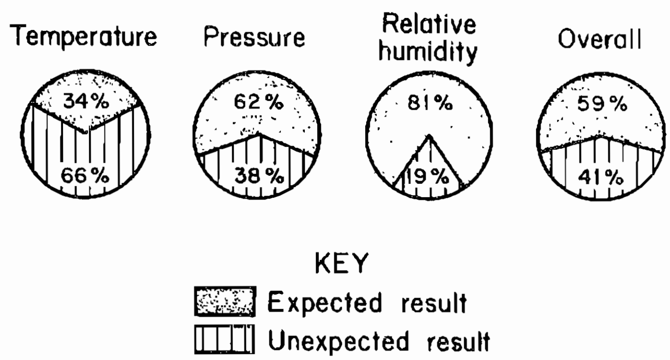


Scatterplot of unexpected results of p_i versus ignition number for two tests.

one test was conducted at 25 °C, the other at 50 °C. A general trend showing the probabilities for the 50 °C test falling above the 25 °C test was expected. Clearly, the opposite is shown in figure 13. The bulk of the 50 °C ignitions fell below a probability of 0.001, but all of the 25 °C ignitions fell above this p_i level on the plot. Here, the cumulative p_i for the 25 °C test was 0.00719; for the 50 °C test, 0.000313. Because the p_i is expected to be greater for a test conducted at an increased temperature, the trend of the data were expected to be the reverse of that shown.

Contradictory results like this can be explained by examining the data files themselves. When comparing a 25 °C test to a similar test at 50 °C, as in the earlier scatterplot, the p_i was expected to increase. When comparing such examples by examining the data files, p_i increased in only 34% of the cases (figure 14). A similar look was taken comparing the 10 psia results to ambient pressure tests and then comparing the ambient pressure tests to 20 psia data. A similar procedure was repeated for the RH tests as well. As shown in figure 14, these results were more predictable than the temperature data. Overall, when changing test environments, the p_i was driven in the expected direction only 59% of the time when temperature

Figure 14



Effect on p_i by shifting test environments.

data were included, but shifted in the expected direction 72% of the time when excluded.

Linear regression analysis was conducted on each test circuit's summary table to create a mathematical model of the data. To simplify the model, temperature, pressure, and RH variables were eliminated where applicable. The values for X_1, X_2, X_3, and X_4 for equations 2 and 3 are listed in table 7. From this, the p_i could be estimated using equation 3.

Table 7.—Linear regression model results

Circuit	X_1	X_2	X_3	X_4	R^2
Capacitor . .	NA	0.1193	-0.0087	4.234	0.480
Inductor . . .	NA	0.1584	NA	-4.831	0.377
Resistor . . .	-0.0228	-0.0623	-0.0145	-0.3226	0.500

NA Not applicable.

As shown in table 7, the resistor circuit model includes all three environmental factors. Because temperature contributed less than 5% of the variance of the dependent variable (log p_i), it was eliminated from the capacitor circuit model. Therefore, the p_i is a function only of pressure and RH. The inductor circuit model goes a step further and eliminates RH as well, indicating the p_i was a function only of pressure.

The R^2 values for each circuit model are also listed in table 7. For the resistor circuit results, 50% of the variance in the log of the p_i is attributable to the test environment. Obviously, an equation that can explain only 50% of the variance of the dependent variable cannot be used in a predictive manner. The results for the inductor and capacitor circuit models were similar.

CONCLUSIONS

The analysis did not consistently confirm the initial hypothesis regarding the effect of the environment on the p_i or produce any consistent trends strong enough to indicate definitive patterns.

Much of the previous research investigating the effects of temperature on ignition energy (*6*) was conducted over significantly wider temperature ranges than studied here, contributing to the initial hypothesis regarding the effect of temperature on the p_i. The testing detailed here was intentionally limited to temperature ranges found in mining environments. It is agreed that an increase in temperature should decrease the required ignition energy and thus affect the p_i at a given energy level. Intuitively, the effect of the temperature may not be as readily apparent as in earlier experiments, either on the ignition energy or the probability of igniting a CH_4-air mixture. For the limited range of temperatures tested, this effect was not significant.

A similar argument may be made for pressure. Earlier tests examined pressures of several atmospheres and their effects on the ignition energy. Such pressures fall well outside the scope of this work. It is suggested that the influence of pressure on the probability would not be as readily apparent when testing over significantly narrower pressure ranges.

As with the temperature and pressure, the relative humidity research also covered a practical range of values, 0% to 70%. In this case, the RH is limited to 100% and thus it is impossible to test at several multiples of the 70% high point investigated here. Because of this, it is believed that the RH results are more likely to agree with other work conducted in this area. The p_i was driven in the expected direction 81% of the time when comparing similar tests conducted at different relative humidities. This is a significant improvement over 62% for pressure tests and 34% for temperature.

It is acknowledged that conducting tests without constant gas flow, as with the 10 and 20 psia tests, may introduce unknown effects on the probability of igniting the CH_4-air mixture. This then would skew the statistical analysis of any test results that also included data generated using the constant flow STA. This would influence only the portion of the analysis devoted to pressure and should not affect the temperature or RH data. Further, it does not explain why the pressure correlation for the resistor circuit research varies so dramatically from the inductor and capacitor results. The author knows of no research that investigated this particular phenomenon; additional research may be warranted in this area.

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